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A LIGHT-GAS GUN FOR ACCELERATION OF PELLETS OF SOLID D₂

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Abstract. A gun has been designed and built to be used for injecting solid D₂ pellets into a small tokamak for pellet-plasma interaction studies. The pellets are formed and accelerated at temperatures close to those of liquid helium. They are propelled with pressurised H₂-gas; the pressure arises when a quantity of solid H₂ placed in the gun barrel behind the pellet is pulse heated. Pellet velocities up to 240 m/s have been obtained. The directional accuracy is better than 0.2° and the repetition rate is one firing every five minutes. The pellet volume is 0.6 mm³ (2·10¹⁹ molecules) while the quantity of propeller gas used is around 12·10¹⁹ molecules.

INIS-descriptors: ACCELERATION, DEUTERIUM, FUEL PELLETS, HYDROGEN, OPERATION, PERFORMANCE, SOLIDS, VELOCITY

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INTRODUCTION

For some years there has been an interest in accelerating pellets of solid hydrogens. The reason for this is that one possible way of bringing fuel of hydrogen isotopes into present plasma physics experiments and into future fusion reactors is to inject it in the form of pellets of solid fuel material. The pellets should be injected at high velocity. For fusion reactors, current theory predicts that such pellets should be injected at velocities of around 10^4 m/s while much lower velocities will be sufficient for present experiments¹⁾.

Hydrogen isotopes are solids only at temperatures below 15 K and the pellets must be fabricated, handled, and accelerated at these low temperatures.

One possible method for accelerating a pellet is the pneumatic one, i.e., the pellet is loaded into a gun barrel and it is then blown out of the barrel by means of gas pressure applied behind it. The propellant should be gaseous at low temperature also; for this reason, only gases such as hydrogen, deuterium, and helium can be used as propellants.

Pneumatic pellet guns have now been built in three laboratories, Oak Ridge National Laboratory²⁾, IPP Garching³⁾ and Risø National Laboratory. The guns are designed to accelerate cylindrical pellets of solid hydrogen and deuterium with diameters of some tenths of a millimeter. At the first two laboratories the propeller gas is pressurised at room temperature and a gas burst is applied to the gun by means of a fast acting valve. Velocities in excess of 1000 m/s have been obtained with a pressure of around 30 bar.

At Risø the propeller gas is pressurised at the low temperature; a small quantity of solid hydrogen is placed in a chamber behind the pellet and the gas pressure is created when the chamber is heated rapidly, forcing the hydrogen to evaporate fast. The

quantity of propeller gas used is fairly small and it can be reduced by decreasing the size of the above-mentioned chamber. The velocities obtained are moderate, to above 200 m/s. However, such velocities will be sufficient for fuelling present plasma experiments.

The Risø gun would be used for injecting pellets into a small tokamak, named Dante, where the interaction between pellet and plasma would be studied⁴⁾.

We shall discuss the Risø gun below, first describing the working principle and after that the gun's operation and the results obtained.

THE WORKING PRINCIPLE

The acceleration method may be demonstrated by means of Fig. 1. A pellet (2) of D_2 is placed in a gun barrel (1), which is held at a temperature close to 4.2 K. Behind the pellet the barrel is terminated by the small propeller chamber⁽³⁾ also kept at a temperature close to 4.2 K. The H_2 for producing the driver

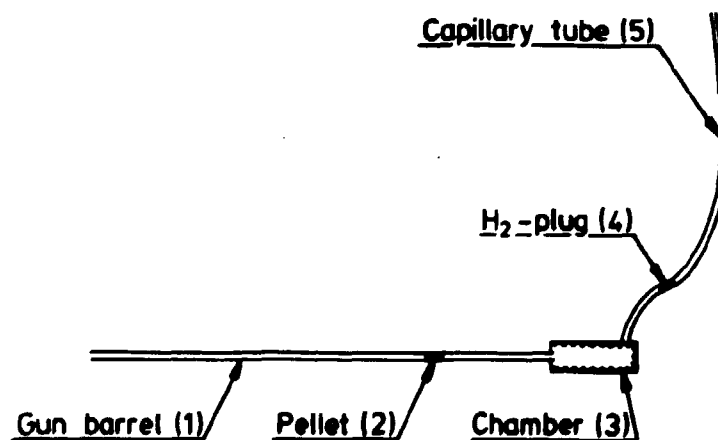


Fig. 1. Schematic drawing to illustrate the acceleration method.

pressure is deposited as a solid layer on the inside wall of this chamber. Just prior to the firing of the gun the barrel (1) is heated; when the barrel reaches a temperature of approximately 12 K the gun is fired by heating the propeller chamber (3) with an energy pulse. This causes the solid H_2 to evaporate; a pressure will then be built up in the chamber and the pellet will be blown out of the barrel.

The H_2 driver gas is led into the chamber (3) through a capillary tube (5) coming from a reservoir at room temperature. It is important that this capillary tube is able to be closed near the chamber (3) so that the driving pressure is not lost backwards through this tube. This closing is accomplished by means of a plug of solid H_2 (4). The temperature is adjustable at a small part of the capillary tube. When the tube is cold the driver gas that was led down from the room temperature reservoir will freeze here to form a plug (4). The plug is removed again by heating and the H_2 gas will then be cryopumped by the inside wall of the chamber, after which it is ready for use as driver gas. A new plug may be formed again as soon as the tube is cold. The closing of the capillary tube need not be very tight and a very small mechanical valve could possibly replace the plug (4).

The Propeller chamber should be heated so quickly that the pressure rises rapidly. At present the chamber is heated by means of an electrical heater wound about it. The heating could also be done by a laser or a particle beam, by induction heating, or by means of an electrical spark or discharge inside the chamber.

The manner in which the pellet is fabricated and placed in the barrel at the low temperature may be illustrated by means of Fig. 2. It shows the D_2 chamber (10) from which a filament of solid D_2 may be extruded together with a second chamber (7), the punch chamber to which the gun is attached. In this chamber the pellet is produced and loaded into the gun barrel.

The D_2 chamber (10) may be filled with D_2 through the tube (12) when the piston (11) is drawn back. The solid D_2 is first

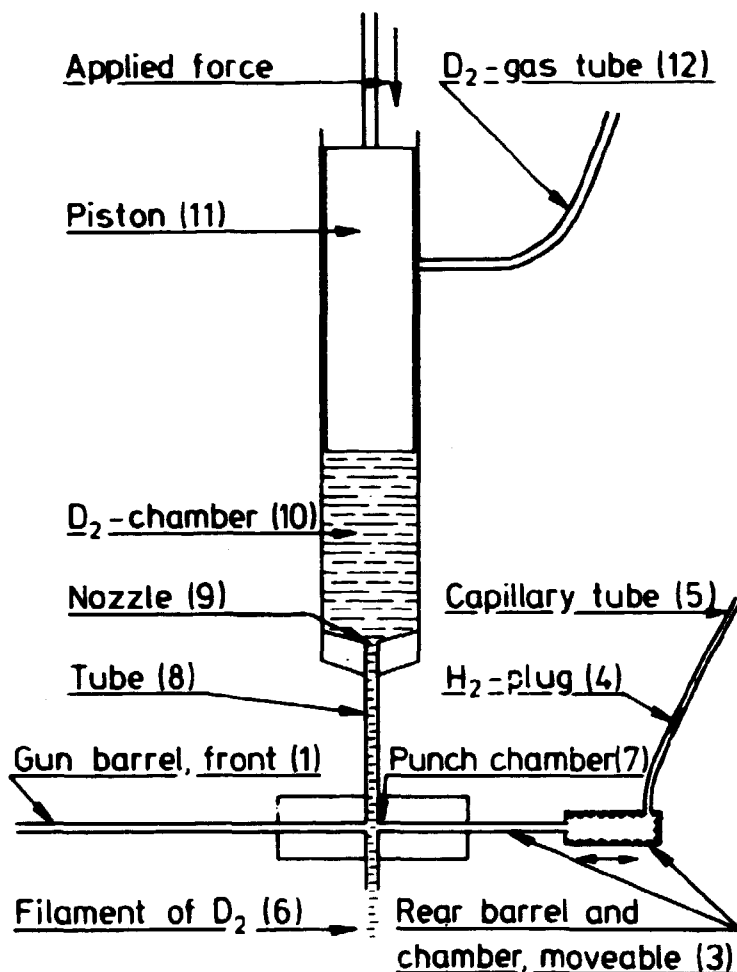


Fig. 2. Schematic drawing to illustrate the fabrication of the pellet and the loading of the gun.

compressed with the piston (11) to form a dense mass. After that a filament of solid D₂ may be extruded through the nozzle (9).

The D₂ chamber (10) may be filled with D₂ through the tube (12) when the piston (11) is drawn back. The solid D₂ is first compressed with the piston (11) to form a dense mass. After that, a filament of solid D₂ may be extruded through the nozzle (9). The filament passes first through a tube (8), then through a channel in the punch chamber (7), and finally appears in the vacuum space (6) below the punch chamber. The gun barrel also passes through the punch chamber. The barrel is placed in a

channel that cuts through the one through which the D_2 filament is led. The barrel is divided into two parts: the front one (1) which is in a fixed position, and the rear one (3) which is movable. The rear barrel is terminated by the propeller chamber. During extrusion the rear barrel (3) is drawn back. After the extrusion of the D_2 filament (6), the rear barrel (3) is moved forward and pushed through the D_2 filament so that a pellet is punched out of the filament and pushed ahead. When the two barrel parts meet, the pellet becomes deformed and is squeezed into the barrel. The gun is now loaded as shown in Fig. 1. At this point it is also ready for firing, as the solid H_2 layer has been already deposited inside the propeller chamber (3) prior to the extrusion of the filament and the loading of the gun.

The solid D_2 must be heated in order that the extrusion can take place. The D_2 chamber (10) is first heated to a temperature of around 8-9 K. After then, the nozzle (9) is heated to around 12 K so that the D_2 close to the nozzle becomes plastic. The solid D_2 can then be extruded when subjected to a pressure of around 100 bar. Also the tube (8) through which the extruded filament passes must be heated to around 12 K. The extrusion is a somewhat tricky process, and there is in fact only a small temperature interval within which it works well. If the D_2 chamber (10), the D_2 , the nozzle (9), and the tube (8) are not heated to the temperatures given, the extrusion cannot be made; the pressure is apparently insufficiently large to force the D_2 through the nozzle and further through the tube. If the temperature becomes too high then the D_2 becomes too soft and the extrusion becomes uncontrollable.

THE GUN SET-UP

The low temperature part of the gun set-up is placed below the bottom of a liquid helium cryostat, Oxford Instruments MD4A, and is protected against thermal radiation by two radiation shields. A photograph of the low temperature part with radiation shields removed is shown in Fig. 3. One can identify the various parts from the schematic drawings in Figs. 1 and 2. The whole gun set-up is placed on a stainless steel bridge (1) solidly attached to the bottom plate of the liquid helium container. The vertical cylinder (10) is the D_2 chamber - Fig. 2 (10). One recognises the gun barrel (8), Fig. 2 (1), the punch chamber (7), Fig. 2 (7), the propeller chamber (6), Fig. 2 (3), and finally the two capillary tubes, the one for H_2 gas (3), Fig. 2 (5), and the one for D_2 gas (11), Fig. 3 (12).

Four copper rods (2) go through the cryostat bottom up into the liquid helium. Various parts of the set-up are anchored thermally to these rods with copper wires or braids.

The electrical heaters are made from manganine wire wound around the part to be heated or merely around a small copper spool (4) and anchored thermally with lacquer. Seven heaters are used with resistances varying from 50 to 140 ohm. The electric power varies from a few mW to around 50-60 mW except for the heater on the driver chamber (6). Here a voltage pulse of 150 to 250 V is applied to fire the gun.

The thermometry makes use of Allan Bradley carbon resistors, 1/4 W resistors with a room temperature resistance of 56 ohm. A resistor is shown in position (9). The eight thermometers in the set-up have not been calibrated.

The wires for both the heaters and thermometers are brought in as a bundle. The bundle is first anchored to the liquid nitrogen container and then to the liquid helium container before it finally appears below the bottom of the latter (12). The total

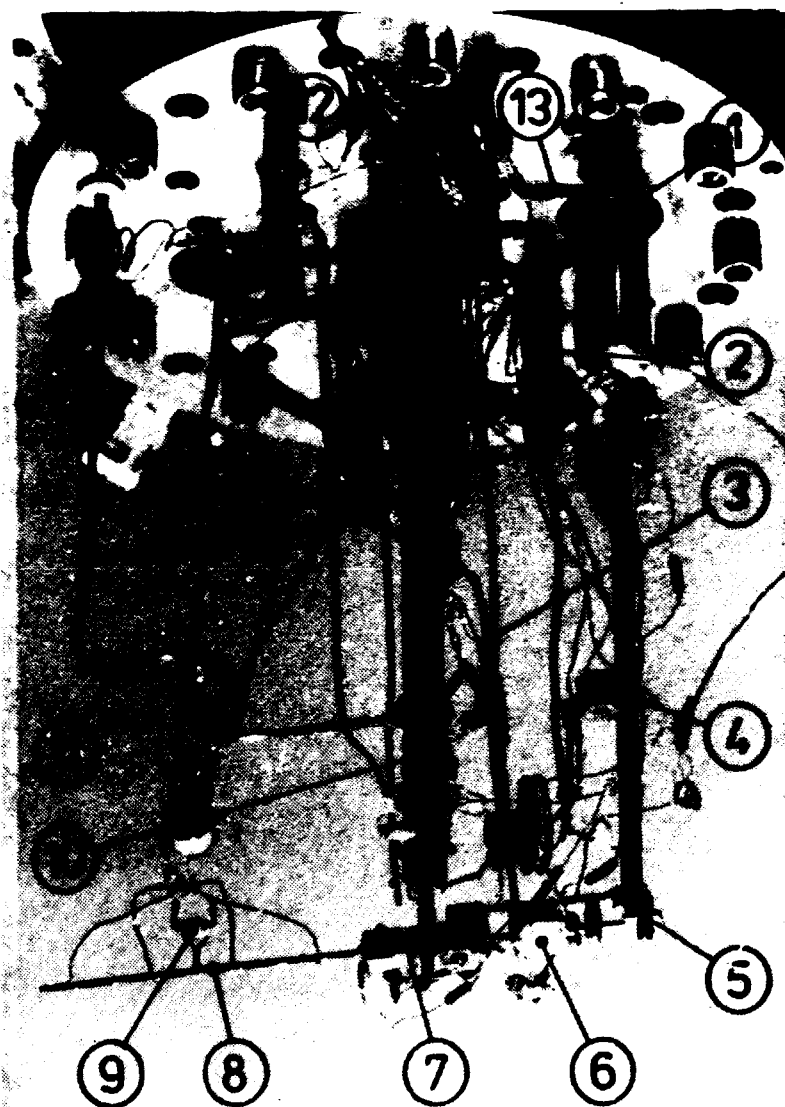


Fig. 3. Photography of the low temperature part of the gun placed below the bottom of the helium cryostat behind radiation shields. (1) is the stainless steel bridge on which the gun system is mounted. (2) is one of four copper rods used for thermal anchoring. (3) is the capillary tube through which H_2 gas is fed to the gun. (4) is a heater and (5) is the eccentric used for moving the propeller chamber (6). (7) is the chamber where the pellet is punched out, and (8) is the gun barrel. (9) is a carbon thermometer. (10) is the chamber in which the solid D_2 is contained, and (11) is the capillary tube for D_2 gas. (12) is the bundle of wires used for heaters and thermometers, and (13) is a copper braid used for thermal anchoring of the piston rod.

length of the bundle is around 3 m. Lacquer-insulated copper wires of 0.12 mm diameter are used.

The wires used for the firing pulse are brought in through another feedthrough and they are anchored thermally by means of platelets of sapphire that are metallized and solderable on both sides.

Tubes, 10 mm in diameter, are led through the cryostat bottom, up through the liquid helium and out through the top plate of the cryostat. The rod, with which force is applied to the piston during extrusion, enters from the top plate through such a tube. The rod is a 3-mm monel tube with 0.2-mm wall thickness, kept in a central position in the large tube with a number of teflon spacers. On the top plate force is applied to the rod by means of pressurized air acting on a piston with a cross-section ten times that of the low temperature piston. The forward position of the piston is controlled with a movable stop, and the position of the stop may be read by means of a transducer for linear movements. The piston rod is anchored thermally to the cryostat bottom with braids (13).

The propeller chamber can be moved forward and backward with an eccentric (5) that is driven with a thin-walled monel tube coming down from the cryostat top through another one of the vertical tubes. The monel tube is turned by an electric motor placed on top of the cryostat.

The two capillary tubes for letting in the gas are brought down from the cryostat top. Both capillary tubes are anchored thermally to the cryostat bottom with copper wires. Gas can then be led down through a capillary tube only when it is heated at the anchoring point.

There are three holes in the radiation shields at the level of the gun. The pellet is blown out through a hole in front of the gun barrel. The pellet gun, the extrusion process, and the propeller chamber may be observed through another hole while the set-up is lit through a third hole. During operation the gun is observed with a small TV-camera.

A measured quantity of H_2 -gas is used for the firing of the pellet. The quantity is measured when a small volume of around 15 cm^3 , limited by two electromagnetic valves, is filled with H_2 -gas from a larger container where H_2 -gas is held at a suitable pressure around 300 mbar. The quantity of firing gas is then 4 to 5 bar cm^3 at room temperature.

The firing is done by applying a voltage pulse of approximately 200 V lasting for 10 ms. The resistance of the heater is close to 90 ohm. An energy of 4 to 5 joule is thus used for firing the pellet.

OPERATION

The operation of the gun is divided into three steps, each of which is run automatically. In the first step, the quantity of driver gas is placed in the movable driver chamber and the capillary tube is thereafter closed with a plug of solid H_2 . The next step, the extrusion, involves the use of several heaters before a filament of D_2 finally appears. The first part of the filament left over in the tube below the nozzle may be too thin because of the heating that takes place during the firing. A fairly long filament should thus be extruded. The extrusion length is controlled with the above-mentioned movable stop that is moved a fixed distance before each extrusion. Unfortunately, this procedure will not produce a constant filament length; it will increase when the quantity of solid D_2 in the chamber is reduced. At least three possible reasons may be mentioned: The first reason may be that solid D_2 is very compressible, and the second that the thermal expansion coefficient of solid D_2 is quite large⁵⁾. The third possible reason concerns the heating of the chamber and the solid D_2 during the extrusion. The heat capacity of the solid D_2 is a considerable fraction of the total heat capacity of the heated system. The solid D_2 will therefore be heated more when the quantity of solid D_2 is reduced. It is

therefore quite useful to monitor the quality of the filament by means of a TV camera, i.e. one observes the uniformity and full thickness of the filament.

In the third step, the pellet is punched out of the filament, it is thereafter pushed forward by the movable gunbarrel and finally squeezed into the barrels when the movable barrel is pressed against the fixed one. The filament is extruded through a tube with 1.2-mm i.d.. The gun barrel has an outer diameter of 1.1 mm and an inner diameter of 0.75 mm. The diameter of the punched pellet thus is 1.1 mm. As one possibility, the whole pellet is squeezed into the barrel. The pellet length should then become approximately $1.2 \times (1.1/0.75)^2$ mm, i.e., 2.5 mm. We shall see later that this is the length of the fixed pellet.

The various procedures in the three steps last 140 seconds. After firing one should then allow a pause in which the propeller gas is pumped away and the gun is cooled. One can then fire the gun every 4 to 5 minutes.

RESULTS FOR THE GUN

The performance of the gun has been tested several times and results exist for its various properties. The data for the gun have been collected in Table 1.

One simple way of detecting a pellet is to let it hit a household-type aluminium foil of thickness 16 μ m. A pellet will make a dent in such a foil. When a pellet hits it sideways the dent is somewhat oblong. In some cases two or more dents appear indicating that the pellet may have broken up into pieces. We have no real explanation for the disintegration of the pellet but we believe that it occurs mainly when the quality of the pellet material is unsatisfactory, i.e. if the extruded filament is deficient in appearance or if the solid D_2 is too warm.

If the filament appears smooth, uniform, and transparent, then the pellet will also normally be satisfactory.

Table 1. A set of data for the pellet gun.

Pellet material - solid D_2
Pellet dimensions - 0.6 mm diam., 2.25-mm long
 $0.62 \text{ mm}^3 - 0.125 \text{ mg} - 2 \cdot 10^{19}$ molecules
Pellet velocity - around 200 m/s, max 240 m/s
Pellet acceleration - around $3.3 \cdot 10^5 \text{ m/s}^2$
barrel length - 60 mm
spread in direction - around $\pm 0.2^\circ$
Energy in firing pulse - 4 to 5 joule
Delay after firing pulse - around 200 to 300 ms
repetition rate - 4 to 5 minutes between shots
Propellant gas - H_2
Quantity of propellant gas - 4 to 5 bar cm^3 at 20°C - around $12 \cdot 10^{19}$ molecules.

The directional accuracy of the gun was tested by shooting it at a foil placed at the end of a long tube. The foil was placed 1.6 m from the gun nozzle and 10 pellets were fired. All pellets hit within a circle of 10-mm diameter. The directional accuracy is thus better than $\pm 0.2^\circ$.

The size of a pellet was measured by shooting it into a known volume. A valve is then closed behind it, and the pressure increase is measured. It was noted that a firing without a pellet gave only a small increase in pressure; thus, only a small part of the propellant gas reaches the volume outside the valve. Eleven pellets were fired and the pressure rises were corrected for the small increases caused by the propellant gas. The mean value of the pellet size was 0.125 mg with a standard deviation of 0.010 mg. The density of solid D_2 is 0.202 g/cm^3 and the volume of the pellet is thus 0.62 mm^3 . This pellet size also includes a part of the cloud following the pellet.

There is a finite time interval between the firing pulse and the appearance of the pellet. This time delay was measured to be several hundred milliseconds; it depended somewhat on the voltage of the firing pulse and on the quantity of driver gas. The smallest delays were obtained with voltages of 200 to 230 volts and a quantity of driver gas of 4 to 5 bar cm³. This gave a time delay of around 250 ms.

It is believed that the pellet is blown out of the gun barrel only when the driving pressure reaches a value large enough to overcome the initial friction between the pellet and the barrel, and that the pellet moves under a somewhat smaller frictional force after that. It takes some time to evaporate the H₂ and build up a sufficient pressure, this is the main cause of the time delay.

The pellet velocity was measured with a system with light guides and photomultipliers. The pellet passed through two light beams placed 10-mm apart and the two light glints from the pellet's passage through the light beams were detected with a photomultiplier and recorded by an oscilloscope.

The pellet velocities were around 200 m/s with some scatter. In one day 39 shots were fired with a mean velocity of 193 m/s and a standard deviation of 18 m/s. The largest velocity recorded to date is around 240 m/s. The length of the active part of the gun barrel is 6 cm. If we assume a constant acceleration for the pellet during the firing then a velocity of 200 m/s corresponds to an acceleration of $3.3 \cdot 10^5 \text{ m/s}^2$.

A new system for velocity measurements now replaces the system used for the first measurements. The pellet here passes through a chamber with two oppositely placed windows. Two light sources are positioned on one side of this chamber and opposite these, two equal vertical slits are aligned, 1-mm wide and 10-cm apart. Behind these slits photodiodes are set. When a pellet passes a slit the light intensity to the photodiode is reduced for a short instant and this dip in intensity is transformed into an electrical pulse. The time distance between the two pulses may

then be measured with an oscilloscope or with a time counter. The velocities obtained agreed quite well with the ones found earlier.

The pellet was also photographed. It was shot through the chamber with the two glass windows and illuminated through one window with a flashlight. The camera, a Beckmann framing camera, was placed at the opposite side of the chamber and focused precisely on the known pellet path. The image is thus a shadow picture. The flashlamp was triggered with a pulse from a photodiode. The pellet velocity should thus be known fairly well in order that the picture be taken at the right time. The exposure time for the camera was 100 ns, and within this time a pellet with a velocity of 200 m/s will move only 0.02 mm. A typical picture is shown in Fig. 4. We see that the length-to-diameter



Fig. 4. A photograph of a moving pellet. The direction of movement is shown with an arrow.

ratio is fairly large, the average value being 3.8. We note also that the pellet is tilted with respect to the direction of movement. If we take the above-mentioned ratio between length and diameter for the pellet and if we assume a pellet volume of

0.62 mm^3 as given earlier, we find the pellet dimensions to be 2.25 mm in length and 0.6 mm in diameter. The pellet length is somewhat larger than the diameter of the filament from which the pellet is formed indicating that the lump of D_2 is deformed to become longer when squeezed into the gun barrel. The volume of the material punched from the filament is 1.1 mm^3 while the volume of a pellet 2.25 mm long and diameter 0.75 mm is 1.0 mm^3 . The whole quantity of material punched from the filament is apparently squeezed into the gun barrel during the loading of the gun. The pellet is thereafter thinned somewhat during the passage through the gun barrel on firing.

CONCLUSION

A pneumatic gun for accelerating pellets of solid D_2 has been built. The gun should be used for pellet plasma interaction studies at Dante; it has now been in operation at Dante for nearly a year.

The velocity is only moderate, around 200 m/s; this low value may be an advantage in conducting pellet plasma studies in a thin plasma.

The quantity of propeller gas is moderate, 4-5 bar cm^3 (3.5 Torr·l) compared to the 10 Torr·l used at the Oak Ridge gun at a working pressure of 10 bars. The quantity of propeller gas can easily be lowered by reducing the size of the propeller chamber. The pumping of the propeller gas is rather fast because the liquid helium bath cryostat used is an effective cryo-pump.

The accuracy of firing is quite high and the gun could thus be useful for injection into a postacceleration device.

A disadvantage is the large time delay. The delay could possibly be shortened partly by reducing the quantity of propeller gas and partly by using a different method for heating the propeller chamber during firing.

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